A&A manuscript no.
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Your thesaurus codes are:
11 (11.07.1; 11.09.1; 11.09.4; 11.19.2; 09.08.1)

ASTRONOMY AND ASTROPHYSICS

The origin of the ionization of the diffuse ionized gas in spirals.

II. Modelling the distribution of ionizing radiation in NGC 157

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Abstract. In this paper we make a quantitative study of the hypothesis that the diffuse Hα emitted from the discs of spiral galaxies owes its origin to the ionizing photons escaping from H II regions. The basis of the models is the assumption that a fraction of the Lyc luminosity from the OB stars within each H II region escapes from the region, leaking into the diffuse gas. A basic input element of any such model is a position and luminosity catalogue in Hα of the H II regions in the galaxy under test, down to a low limiting luminosity, and we had previously produced a catalogue of this type for NGC 157. An initial family of models can then be generated in which the Lyc escaping from an H II region is parametrized in terms of the observed Hα luminosity of the region and the escaping fluxes allowed through the diffuse disc gas. These models can then be refined using a measured map of H I surface density to effect the down-convertion of the Lyc to Hα. For NGC 157 an H I map was available. Although its moderate angular resolution did limit the accuracy with which we could test our models, the predicted diffuse Hα surface brightness distributions from our models were compared with the observed distributions showing that, in general terms, the hypothesis of density bounding for the H II regions allows us to predict well the spatial distribution of the diffuse ionized gas. In the model yielding the best fit to the data, the regions of lower luminosity lose a constant fraction of their ionizing flux to their surroundings, while for H II region luminosities above a specific transition value the ionizing escape fraction is a rising function of the Hα luminosity.

Key words: Galaxies: general–Galaxies: individual (NGC 157) –Galaxies: ISM–Galaxies: spiral–ISM: general–ISM: HII regions.

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1. Introduction

Although the diffuse component of Hα emission from a disc galaxy has low surface brightness, the integrated Hα luminosity emitted by a galaxy in this component is relatively high, of order 50% of the total radiated by the galaxy, for late-type spirals (e.g. Ferguson et al. 1996; Hoopes et al. 1996). In Zurita et al. (2000, hereinafter Paper I) we made a detailed study of 6 galaxies in which we quantified this diffuse component and its geometrical distribution across the face of each galaxy. Supporting an observation previously noted by Walterbos & Braun (1994) and Ferguson et al. (1996), we found a very clear spatial correlation between the H II region emission in Hα and that of the diffuse emission, leading to a prima facie case for considering that OB associations are the sources or, at least, the principal sources of the ionizing photons which eventually reach and ionize the diffuse gas in the disc as a whole. Quantitatively, it appears that the stars in these associations can emit sufficient photons above the Lyman limit to maintain the diffuse component ionized, as well as the gas within the H II regions of the galaxies observed, and are an obvious choice for the primary cause of the diffuse Hα. They are clearly collectively more luminous in the Lyman continuum (Lyc) that the population of white dwarfs, for example. However, it has never been entirely clear that a major fraction of Lyc photons can escape from the immediate surroundings of an OB association: its H II region, and even less clear that an escaping photon can be transmitted across distances of order a kiloparsec, from the nearest OB associations to zones in the diffuse disc gas from which significant surface brightness in Hα is observed. This difficulty was a key motive in leading Sciama (1990) to propose his decaying neutrino model for the ionization of the diffuse component, although recent EUV observations of the interstellar medium (ISM) close to the

Sun (Bowyer et al. 1999) appear to have ruled out this model.

In the case of the Galaxy, several models have been proposed in which transport of ionizing photons over distances of order 1 kpc is shown to be viable, at least in the neighbourhood of the Sun (Miller & Cox 1993; Dove & Shull 1994). The fact that locally we can quantify the OB stars, and can map the ionized and neutral hydrogen in detail, means that models of this sort are useful since they can be well compared with data.

There are two main physical reasons why ionizing photons can escape from H II regions and transit large distances in spite of the large ionization cross–section of neutral H. The principal reason is the inhomogeneity of the ISM. It is well established, for example, that although the r.m.s. electron density in a luminous H II region is of order 1-5 cm^{-3} (e.g. Kennicutt 1984; Rozas et al. 1996b, 1999), the electron density determined locally via emission line ratios is of order 100 cm^{-3} (e.g. Zaritsky et al. 1994). This is interpreted (Osterbrock & Flather 1959; Osterbrock 1989) as reflecting the presence of dense knots (or clumps of gas) which are the sites of virtually all the optical line emission from the H II region, within an ambient volume of much lower density gas. The ratio of the volume of dense gas to the total volume of the region is embodied in the "filling factor", which may be defined simply as the ratio of the two volumes. This rather simple scheme of dense clumps in a sparse medium (i.e. the inhomogeneous structure of the ISM) is backed by the general theory of thermal equilibrium in the interstellar medium, treated classically by Field, Goldsmith & Habing (1969): a two–phase model, with a warm substrate at T$\sim$10000 K, and cool dense clumps at T<100 K, then by Cox & Smith (1974): a three phase model including also the effects of supernovae and a component at T>100000 K, and McKee & Ostriker (1977), who produced a more complete three–phase model against which much observational material within the Galaxy has subsequently been compared. It can be demonstrated (see e.g. Spitzer 1978) that in the ISM distinct phases should co-exist in pressure equilibrium, while states of intermediate density and temperature are unstable and decay rapidly. The scenario of dense clouds with $N_e \sim 100$ cm^{-3}, surrounded by a much lower density substrate, with $N_e \lesssim 1$ cm^{-3}, and infiltrated with high temperature fully ionized plasma having $N_e < 10^{-2}$ cm^{-3} has been well verified by many detailed measurements in the local interstellar medium (LISM) within a few hundred parsec of the sun (Trapero et al. 1995, 1996). The high density clouds contribute a major fraction of the mass, but occupy a minor fraction of the volume (Trapero et al. 1996). Studies by Berkhuijsen (1999) in the Galactic ISM show that this type of inhomogeneous structure prevails over a wide range of mean ISM density and temperature. There is evidence for this structure also in external galaxies, as shown by Braun (1997) for a sample of the 11 nearest spiral galaxies beyond the Local Group. The fact that an inhomogeneous ISM offers a lower effective volume absorption coefficient for Lyc photons than a homogeneous medium is easy to demonstrate, and a very general result, common to many types of transfer problems.

The second effect permitting a fraction of Lyc photons to have free paths on kpc scales is a secondary consequence of the inhomogeneity of the LISM. Since the recombination rate of ionized hydrogen is proportional to the product of the electron and proton densities, i.e. effectively to N_e^2 or to N_p^2, a given luminosity in Lyc photons can maintain ionized a volume of plasma inversely proportional to the square of the density. To see how this affects the range of a Lyc photon, we can express this relation in terms of the Strömgren radius (the radius of a fully ionized plasma sphere maintained by a specific ionizing source). The Strömgren radius must vary as $N_e^{-2/3}$ (or $N_p^{-2/3}$). In an inhomogeneous medium, this radius can be used as an upper limit to the mean free photon path, if N_e is taken as the electron density of the low density phase of the ISM. An O3 star yields a Strömgren radius of 140 pc in a homogeneous medium of mean density N_p=1 cm^{-3} (calculation scaled from values in Vacca et al. 1996). The corresponding radius in a medium of N_p=0.1 cm^{-3} will be 650 pc, so that a source equivalent to 4 O3 stars will yield a radius of $\sim$1 kpc in a medium with this density. The net result is that in an inhomogeneous medium an ionizing source with a strong flux effectively "burns" its own long free path through the low density phase; this is the same physical effect as that analyzed by Miller & Cox (1993), though it is certainly applicable to more circumstances than those caused only by supernovae (see Mckee & Ostricker 1997) in yielding the initial low density ionized phase.

We are aware that there are almost certainly other sources of energy input into the DIG, which were cited in Paper I. These have been inferred from measurements of emission line ratios, notably [S II]/Hα,[N II]/Hα, [S II]/[N II] and [O III]/Hα, as discussed by a number of authors, including Reynolds (1984), Reynolds, Haffner & Tufte (1999), Greenawalt, Walterbos & Hoopes (1997), Hoopes & Walterbos (2000), Collins & Rand (2000), and also from the presence of non–thermal velocity widths of emission lines (e.g. by Minter & Balser 1999; Tufte, Reynolds & Haffner 1999). In the present context, however, we are concentrating our attention on what we believe to be the principal ionizing source of the DIG, i.e. Lyc escape from H II regions, and our results tend to confirm that this approach is useful in practice.

In modelling an external galaxy to see whether the OB stellar sources can account for the observed surface brightness morphology of the diffuse Hα–emitting gas, it is not possible observationally to resolve structure within the ionized gas (nor in the neutral gas). This means that a microscopically realistic model of how the inhomogeneity affects the transfer of ionizing radiation cannot be tested

fairly. In the present paper we have adopted a macroscopic approach, assuming large–scale homogeneity, so that an absorption coefficient with an effective mean value can be applied on scales larger than tens of parsec. The range of trial values for this coefficient is based on simplified general transfer calculations with realistic photon fluxes and gas densities. This method has enabled us to make useful comparisons between theory and observation, which go as far as is warranted at present by the data, notably in the absence of H I surface density maps at high spatial resolution. The basic aim here is to go at least far enough to show whether or not the hypothesis of the OB associations as the chief ionizing sources for the DIG can be discarded.

2. The data used for the models of NGC 157

In Paper I we published a careful analysis of the observed diffuse Hα from the discs of 6 galaxies, but we have chosen here only one of these, NGC 157, to model the DIG surface brightness distribution in Hα. This is because it is the only one of our objects for which we have an H I map with anything approaching fully adequate angular resolution.

2.1. The Hα image

The observations for this image, and their analysis, were described in Rozas et al. (1996a). The galaxy was observed at the 4.2 m William Herschel Telescope on La Palma, under good seeing conditions. The seeing in the reduced final image was $0.8''$. A luminosity function in Hα for the H II regions was extracted and presented in Rozas et al. (1996a), after cataloguing 708 H II regions in total. The criterion for considering an image feature as an H II region was that it must contain at least nine contiguous pixels each with an intensity of at least three times the r.m.s. noise of the local background (see Rozas et al. 1996a for further details).

In Paper I we showed the surface brightness distribution of the diffuse Hα component, and inferred its integrated luminosity, its radial distribution within the galaxy and the fraction of the total galactic Hα in diffuse emission, as a function of radius and in the galaxy as a whole.

The method employed to separate the Hα flux emitted from the H II regions from that of the surroundings has benefitted from our previous cataloguing of the H II regions. In the first place, we constructed masked images in which the Hα surface brightness of those pixels occupied by the catalogued H II regions was set to zero (i.e. we assumed that there is no diffuse emission over each H II region), considering a circular approximation for the shape of each H II region. After this, to take into account that H II regions are not truly spherical, a surface brightness cut–off equal to 73 pc cm^{-6} was employed over the masked images to avoid including in the DIG any residual emission from the H II regions. A lower estimate of the total Hα emitted from the DIG of the galaxy was then obtained by integration of this masked image. The upper estimate was obtained in a similar way, but including an estimate for the diffuse emission above each H II region. The detection thresold for the DIG of NGC 157 was 1.0 pc cm^{-6}. Detailed explanations of the isolation procedure and uncertainties in the measurements of the total Hα emission from the DIG are given in Paper I.

As stated in paper I, we have not made any correction, either for the dust extinction within the emitting galaxy, or for Galactic extinction.

2.2. The H I map

NGC 157 was observed by Ryder et al. (1998), with the VLA using the C and D configurations. The on–source exposure time with the C–array was 3.7 hours, and with the D–array 2.8 hours. The two data sets were processed separatedly and combined. The total velocity range covered was 581 km s^{-1} with a channel increment of 5.2 km s^{-1}. Two distinct data cubes were produced, using different weightings in the imaging process (see Ryder et al. 1998 for a detailed description of the observations, the reductions and the processing tasks). Here we used the H I surface density map obtained from the cube produced using uniform weighting, which yields better angular resolution than natural weighting. The beam width at half power for the map used here is $18''\times12''$ and the r.m.s. noise 1.3 mJy beam^{-1}.

3. Descriptions of the models for the propagation of the ionizing photons

In the present section we explain the simplified theoretical models which predict the ionizing photon distribution in the disc of the galaxy NGC 157, assuming that they are produced within and escape from the catalogued H II regions. Different laws governing the escaping photon fraction and the absorption as they transit the ISM yield a set of models. In these models, each measured H II region is taken as an ionizing source and fraction of the measured ionizing flux within each region is taken as the luminosity of the escaping flux, available to maintain the ionization of the DIG. The Hα surface brightness of the DIG is computed by allowing the Lyc flux from a source to radiate within a thin disc in an inverse square regime of dilution. In the simplest case, the fields from all the observed H II regions are co–added and the result compared to the observed surface brightness distribution. Implicit in this procedure is that the DIG surface brightness in Hα is linearly proportional to the underlying Lyc field, which is the same as assuming that the disc consists of a slab of HI, whose properties do not vary from place to place. It is clear that the observed Hα surface brightness must be the projection of a three–dimensional DIG column onto the plane of the galaxy observed (if it is face–on). Given that the scale–height of the DIG, as shown within our Galaxy

(Reynolds 1989) is of order 1 kpc, and that even the largest H II regions do not project more than some three hundred pc out of the mid-plane, the simplified geometry employed here will yield a useful result for the integrated columns perpendicular to the plane viewed in a generally face–on direction.

A second step in bringing the model into better relation with the observations is to use the observed H I surface density distribution to modulate the Lyc flux, taking a uniform mass absorption coefficient to represent attenuation by gas plus dust extinction, and a third step is to take the product of the previously computed Lyc field and the H I surface density for the predicted Hα distribution, assuming that the resulting surface brightness is the result of the irradiation of local neutral hydrogen by an incident ionizing field. The results from this type of modelling are expected to be useful approximations provided that the ionized column density is not a large fraction of the neutral column density, an assumption which we tested for NGC 157, and which holds everywhere in the disc outside the H II regions (see Sec 4).

An interesting invariance relation which helps to account for the relative lack of apparent structure in the DIG, in spite of the assumed inhomogeneity of the clouds which compose it, and which also helps to account for the fact that an essentially two–dimensional approximation can satisfy a three dimensional flux distribution, is that the emission measure in Hα emitted by an optically thick cloud irradiated from outside is independent of the cloud density, and depends only on the intensity of the irradiating field. We can show this quite directly. In an optically thick case, where all the incident photons are absorbed, the intensity of the recombination radiation emitted (in the present case Hα) can be related to the incident ionizing radiation, using the "on the spot" approximation (Osterbrock 1989), in which any ionizing photons emitted by the ionized gas are reabsorbed locally. In this case, the number of ionizations per unit volume of the cloud in which the external flux has penetrated will be equal to the number of recombinations to excited levels of the hydrogen:

$$N_{H^\circ} \int_{\nu_\circ}^{\infty} F_\nu \, a_\nu \, d\nu = N_e \, N_p \, \alpha_B(H^\circ, T) \qquad (1)$$

where the atomic hydrogen density, the electron density and the proton density are denoted respectively by N_{H°, N_e and N_p, where $\alpha_B(H^\circ, T)$ is the recombination coefficient to excited levels of hydrogen, F_ν is the number of incident photons per unit area, time and frequency interval, and a_ν is the ionization cross–section for hydrogen by photons with energy $h\nu$ above the Lyman limit $h\nu_\circ$. If we integrate Eq. 1 down to the depth within the cloud within which all the incident radiation is absorbed (the optically thick case) using the equation of radiative transfer in the form:

$$dF_\nu / ds = -N_{H^\circ} a_\nu \, F_\nu \qquad (2)$$

we have:

$$\int_{\nu_\circ}^{\infty} \{ \int_{F(s=0)}^{F(s=L)} -dF_\nu \} \, d\nu = \alpha_B(H^\circ, T) \int_0^L N_e \, N_p ds \quad (3)$$

The integrated intensity of the emitted Hα from a column of length L along which the electron and proton densities are given by N_e and N_p respectively is proportional to the integral on the right hand side of Eq. 3, conventionally termed the emission measure, EM, of the column. We can rewrite Eq. 3, incorporating the appropriate numerical constants, in the simpler form;

$$F(s=0) = A \; \alpha_B(H^\circ, T) \; \mathrm{EM}(\text{in pc cm}^{-6}) \qquad (4)$$

where $F(s=0)$ is the incident flux in the surface of the cloud, A is a constant, whose numerical value for $F(s=0)$ in units of phot. s^{-1}cm^{-2} is 3.08×10^{18} and $\alpha_B(H^\circ, T)$ does not show strong dependence on T in the range normally found in the warm ionized ISM ($\alpha_B \sim 2.59 \times 10^{-13}$ cm^3 s^{-1}).

Eq. 4 implies that irrespective of the total column depth of the cloud, if it is optically thick to ionizing radiation it will develop an emitting skin for which the Hα intensity will be proportional to the ionizing flux. Thus, seen from above, a set of H I clouds with varying hydrogen column density bathed from the side in uniform ionizing radiation will all show the same surface emissivity. This result accounts in large part for the uniform appearance of the diffuse Hα from a galactic disc, in spite of the intrinsic clumpiness of the substrate. This result does not hold for an optically thin cloud, so that the net diffuse emission from a projected disc should not be entirely free from local variations. The result above also implies that, if the ionization of the DIG is indeed due to OB stellar clusters, the observed mean EM in the disc relatively far from ionizing sources should show a rough proportionality to the H I column density. This is because if the H I is in discrete clumps, optically thick to Lyc (but not in general to Hα), the integrated EM averaged over a column should be proportional to the integrated surface area of clumps per projected column cross–section, which will be a rising function of the integrated column density in HI, although the exact relation will depend on the details of the clump distribution. These considerations for the relation of the observed EM of the DIG to the gas distribution in the disc are valid for whichever detailed hypothesis we adopt about the relation of the observed Hα in the H II regions to their ionizing luminosities in Lyc.

3.1. Constant escape fraction (case A)

The simplest assumption to make when considering H II regions as the zones of origin for the photons which ionize the DIG is that a constant fraction of the Lyc from the OB stars in any H II region escapes from the region into the surrounding diffuse gas. A number of previous

studies have suggested that a significant fraction of the total ionizing luminosity of OB stars can and does escape from their surrounding H II regions, and is available to ionize the diffuse ISM. This conclusion is supported by the geometrical correlation observed between the sites of H II regions and the surface brightness of the DIG (Ferguson et al. 1996). The escaping flux from a given H II region was not quantified by Ferguson et al. (1996) who did not produce a photometric catalogue of H II region luminosities, though their estimate of the total flux required to ionize the DIG was comparable to our estimates in Paper I, i.e. of order 50% of the total for the whole disc. McKee & Williams (1997), estimated that approximately 30% of the ionizing photons observed within the H II regions of the Galaxy, defined by the extent of their cm wavelength continuum emission, in fact escape from the H II regions. In general, the number of ionizing photons absorbed in an H II region observed in Hα will be higher than that absorbed only within the bright central zones, which define the region at cm wavelengths, but it is not apparent how to define reliably a core–halo boundary in Hα. We chose a 30% constant escape fraction as our starting point for the "constant escape fraction models" of NGC 157. In these models, each measured H II region is taken as an ionizing source and a constant fraction of the measured ionizing flux within each region is taken as the luminosity of the escaping flux available to maintain the ionization of the DIG. The Hα surface brightness of the DIG is computed by allowing the Lyc flux from a source to radiate within a thin disc in an inverse square regime of dilution.

3.2. Density bounding at high luminosity (case B)

In Paper I we outlined a possible model for the escape of ionizing photons from H II regions, in which essentially all the Lyc escapes from the regions of highest luminosity, i.e. those with observed luminosity in Hα, $L_{H\alpha}$, greater than a critical transition value L_{Str} (the "Strömgren transition luminosity"). This follows from a series of studies in which evidence has accumulated pointing to the fact that H II regions of very high luminosity are density bounded, and that an increasing fraction of their Lyc fluxes escape as their luminosities increase (Rozas et al. 1998; Beckman et al. 2000). We have developed a general parametric formulation showing the dependence of the escaping ionizing luminosity as a function of the physical parameters of the H II regions with Hα luminosity greater than L_{Str}, whereas no escape of Lyc is assumed for H II regions in which $L_{H\alpha} < L_{Str}$ in this case B.

Let $N_{H\alpha}$ be the number of ionizing photons per unit time from OB associations which ionize the surrounding cloud and are down–converted in Hα emission within an H II region[1]. Assuming that an H II region contains gas in small condensations or clumps with electron density ρ_c, $N_{H\alpha}$ can be expressed as:

$$N_{H\alpha} = \frac{4\pi}{3} n \alpha^{eff}_{H\alpha} {\rho_c}^2 \phi \, R_s^3 \qquad (5)$$

where $\alpha^{eff}_{H\alpha}$ is the effective Hα recombination coefficient, ϕ is the filling factor (or fraction of the total volume occupied by the condensations, as explained above), n is the number of Lyc photons necessary to yield one Hα photon (n=2.233 Lyc photons/Hα photon for T$\sim 10^4$ K; Osterbrock 1989) and R_s is the Strömgren radius of the H II region.

The ionized mass of the H II region can be written as:

$$M_{H^+} = \int m_H \phi \rho_c dV = \frac{m_H}{n\alpha^{eff}_{H\alpha}} \frac{N_{H\alpha}}{\rho_c} \qquad (6)$$

where m_H is the mass of an atom of hydrogen and the integral is performed over the entire volume (V) of the H II region.

Density bounded H II regions are fully ionized, so for these regions the mass of the placental cloud (M_{cl}) is equal to the mass of ionized hydrogen in the H II region. Combining Eqs. 5 and 6 and normalizing the quantities (which will be noted with ˆ) by their value at the Strömgren transition, we find that

$$\hat{N}_{H\alpha} = \frac{N_{H\alpha}}{(N_{H\alpha})_{Str}} = \frac{\rho_c}{(\rho_c)_{Str}} \frac{M_{cl}}{(M_{cl})_{Str}} = \hat{\rho_c} \, \hat{M}_{cl} \qquad (7)$$

This equation holds for density bounded H II regions.

In Beckman et al. (2000) a simplified scaling calculation is presented, in which the required relation between cloud–mass and the ionizing luminosity (L_i) emitted by a young cluster of stars which has formed in a placental cloud of mass M_{cl} is given by

$$L_i = k(M_\star)^\alpha = k j^\alpha (M_{cl})^{\alpha\epsilon} \, , \qquad (8)$$

where k, j are constants that depend principally on the metallicity (Beckman et al. 2000) and $M_\star$ is the total stellar mass in the OB association. The index α represents a parametrized relation between L_i and the stellar mass ($M_\star$) in the cloud, while the index ϵ is the parametrized relation between the the stellar mass and M_{cl}. The condition that the rate of production of ionizing photons fully ionizes and overflows the placental cloud implies that $\alpha\epsilon$ should be greater than unity (see Beckman et al. 2000 for details). Observational evidence showing that $\alpha\epsilon$ should indeed be greater than unity was reviewed in Beckman et al. (2000), and a value close to 1.6 was adopted as the

[1] The relation between $N_{H\alpha}$ (number of ionizing photons per unit time from the OB associations down–converted in Hα emission) and the observed luminosity in Hα of an H II region, $L_{H\alpha}$ is $N_{H\alpha} = n L_{H\alpha}/(h\nu_{H\alpha})$, where $h\nu_{H\alpha}$ is the energy of an Hα photon and n=2.233 Lyc photons/ Hα photon for T$\sim 10^4$ K (Osterbrock 1989).

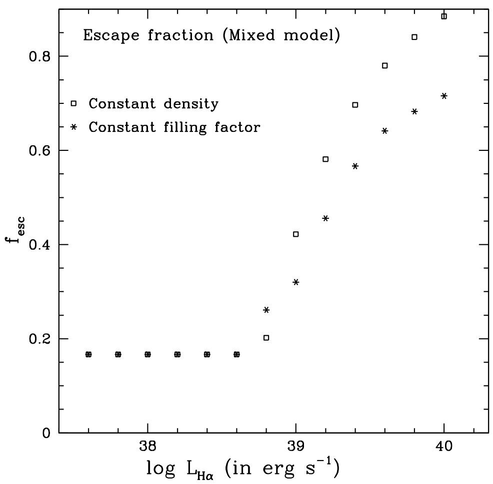

Fig. 1. Fraction of the total ionizing photon flux within an H II region, which escapes from it in the mixed model C (see text for details). The relation of f_{esc} (in the figure) to f (Eq. 10) is given by $f_{esc}=f/(1+f)$. Approximately 80% of the total ionizing radiation escapes from the most luminous H II regions in NGC 157 in this model (i.e. nearly 4 times the ionizing luminosity down–converted to Hα emission within the region).

best estimate. Combining Eqs. 8 and 7 and normalizing to $(L_i)_{Str}$:

$$\hat{L}_i = (\hat{M}_{cl})^{\alpha\epsilon} = (\hat{N}_{H\alpha})^{\alpha\epsilon} \hat{\rho_c}^{-\alpha\epsilon} \quad (9)$$

Under these conditions we can compute the escape fraction (f) of ionizing photons down–converted in Hα ($N_{H\alpha}$) which escapes from the most luminous regions as a function of the observed luminosity in Hα:

$$f = \frac{\hat{L}_i - \hat{N}_{H\alpha}}{\hat{N}_{H\alpha}} = (\hat{N}_{H\alpha})^{\alpha\epsilon-1} \hat{\rho_c}^{-\alpha\epsilon} - 1 = = (\hat{L}_{H\alpha})^{\alpha\epsilon-1} \hat{\rho_c}^{-\alpha\epsilon} - 1 \quad (10)$$

To estimate f it is necessary to know how the clump density varies with the H II region luminosity. Measurements of Hα surface brightness alone will not allow us to detect whether ρ_c is increasing as the luminosity increases, but do tell us (see Rozas et al. 1996b, 1998) that the product $\rho_c \phi^{1/2}$, which is equal to $< N_e >_{rms}$, increases by a factor close to 2 between the Strömgren luminosity and the luminosities of the brightest regions, and enables us to use Eq. 10 to set bounds to the predicted escaping photon flux from density bounded regions, as a function of luminosity. An example of this is given in Fig. 1 (for luminosities greater than L_{Str}) in which the two limiting cases of varying ρ_c and fixed ϕ or varying ϕ and fixed ρ_c are taken and used to predict the escape fractions of ionizing photons versus luminosity. Fig. 1 shows f_{esc}, which is the fraction of the total ionizing photon flux which escapes from the H II region. Note that if f (Eq. 10) is the fraction of ionizing photons down–converted to Hα ($N_{H\alpha}$) which escapes from the H II region, the relation between the two quantities is given by $f_{esc}=f/(1+f)$.

In the models, to maintain the family of calculated cases as simple as possible, we maintained $\alpha\epsilon$ at a constant value of 1.6, and ρ_c constant, varying ϕ in order to reproduce the range of observed surface brightness in Hα v. $L_{H\alpha}$ found for the regions in NGC 157 by Rozas et al. (1996b). We note that at the highest luminosities the escape fraction rises to values well above 0.5, which means that more than 50% of the Lyc photons escape from the region. We can use the interpolated curve in Fig. 1 to compute an escape fraction from each H II region in the catalogue of regions for the galaxy, so that the absolute luminosity in ionizing photons escaping from each region is then tabulated, and can be used as input to model the production of the diffuse Hα in the same way as for the models with constant escape fraction, as explained in the preceding Sec. 3.1.

3.3. Mixed models (case C)

In this model we assume that the major contribution of ionizing photons available to ionize the DIG comes from the most luminous H II regions (those with log $L_{H\alpha} \gtrsim 38.6$, in erg s^{-1}), whose escape fraction is given by Eq. 10, but a minor contribution escapes from the less luminous regions (with log $L_{H\alpha} < 38.6$, in erg s^{-1}), for which a constant escape fraction of ionizing photons is assumed (f=20%).

Inspection of the Hα image of NGC 157 showed us that the diffuse component is relatively strong near an H II region, and that this observational correlation appears to hold not only for the most luminous regions, but also for regions with luminosities below $L_{H\alpha}=L_{Str}$. The implication is that even those regions with lower luminosities are leaky. Such an inference is entirely plausible given the clumpy structure of any interstellar cloud and, in particular, of the clouds which make up the H II regions. Proof of the clumpy nature of the regions is found by comparing the r.m.s. electron density in a region (Rozas et al. 1996b, 1999, 2000) obtained from a diametral emission measure in Hα with in situ measurements of electron density obtained via line ratios (Zaritsky et al. 1994), as explained above in Sec. 1. Relatively crude models using this structure give as a result an escaping fraction for the Lyc produced by their OB populations, a fraction which should vary little if the density structure of a region depends little on its luminosity. Measurements of filling factors show that, at any rate for $L_{H\alpha} < L_{Str}$ this condition appears to hold rather well. However, as explained above in Sec. 3.1 at the highest luminosities the r.m.s. electron density shows higher values (Rozas et al. 1996b, 1999, 2000) which we interpret as due to an increased effective filling factor, which in turn is explained if the clumps near the stellar sources become fully ionized, releasing more Lyc to ionize clumps

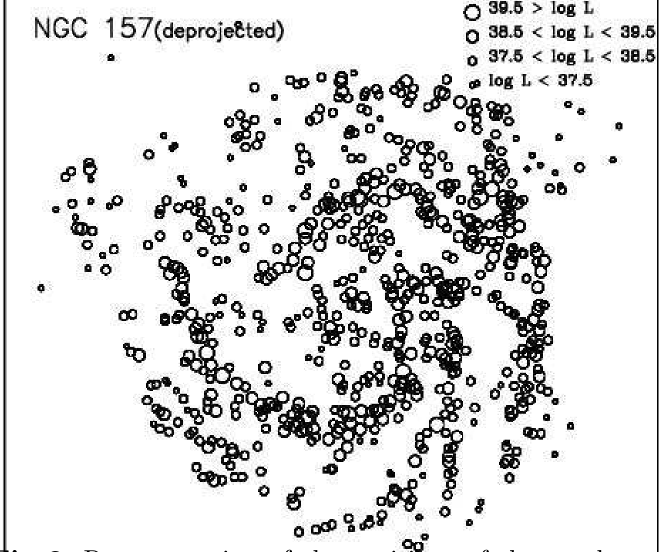

Fig. 2. Representation of the positions of the catalogued H II regions in the deprojected disc of NGC 157. The vertical direction of the plot is coincident with the major axis of the galaxy. Symbols show ranges of log $L_{H\alpha}$.

further out within the region. In this model each individual clump behaves as an ionization bounded or a density bounded system, according to the ionizing luminosity of the region, and the distance of the clump from the star cluster. The H II region as a whole then starts to leak a higher fraction of its Lyc luminosity when the inner dense clumps become density bounded, which will occur for regions of high stellar luminosity. Without going into further detail, we have taken this into account empirically in our termed "mixed models" by using a constant escape fraction for $L_{H\alpha} < L_{Str}$ and an increasing escape fraction for $L_{H\alpha} > L_{Str}$, following Fig. 1.

4. Comparing observations with the model predictions

4.1. Models with no computed in–plane extinction

The basis for all the models is the positional and luminosity catalogue of all the detected H II regions in NGC 157[2]. In Fig. 2 we show this in display form, i.e. the positions and luminosities of all the regions used in the models are indicated in this map deprojected into the plane of the sky. To use the regions as sources for the diffuse component, we first apply the escape factor appropriate to the model: constant factor (case A), pure density bounding above $L_{H\alpha}$=L_{Str} (case B), or mixed model (case C), to each and every one of the regions. Treating each region as a point source with effective Lyc luminosity equal to that corresponding to its measured Hα output, multiplied by the escape factor, we then model the diffuse emission using a set of assumptions of increasing complexity.

In this section we assume a uniform HI layer of constant thickness. In the simplest case, we compute a flux density $I_j(x,y)$ at a point (x, y) in the disc due to a region (j) emitting D_j escaping photons per second, via:

$$I_j(x,y) = \frac{D_j}{4\pi[(x-x_j)^2 + (y-y_j)^2]} \tag{11}$$

[2] For the criteria of the lower limit of detectability the reader is referred to Rozas et al. 1996a.

where (x_j, y_j) are the coordinates of the region selected. We then sum over all the regions to obtain the final ionizing photon flux density map from the contribution of all H II regions:

$$I(x,y) = \sum_{j=0}^{N} I_j(x,y) \tag{12}$$

where N is the total number of catalogued regions (weaker regions would make a negligible impact on the result using any of the assumptions taken in this work (and can genuinely be neglected). A sample result of computing $I(x, y)$ in this way is shown in Fig. 3a where we have taken the simplest case, i.e. a hypothetically constant fraction of escaping photons for the D_j values. We have compared this computation directly, in Fig. 3(right) with the deprojection into the plane of the sky of the diffuse Hα measured in NGC 157, and we can see that the result is to say the least encouraging. All the broad intensity and morphological features of the diffuse Hα are reproduced, although inspecting the fine details we can pick out certain discrepancies. We should state now that in the rest of the discussion rather than deproject the observed diffuse light distribution into the plane of the sky we will project the model into the plane of the galaxy disc, as this is an operation which of course is not affected by low signal to noise ratio.

The fact that the morphological agreement between model and observations is so good is perhaps a little surprising, since the conditions imposed are so simple. Without further refinement we can use this result to criticize the hypothesis that the diffuse Hα is originated by decaying massive neutrinos, although this model by Sciama (1990) has been already found wanting via direct EUV observations (Bowyer et al. 1999). We can do this by comparing the measured distribution of H I column density in Fig. 5 with the Hα distribution and model prediction. The H I density contours for NGC 157 (Ryder et al. 1998) have been overlaid on the Hα image of the galaxy. The angular resolution is poor by Hα standards, but we can see clearly that zones of high surface brightness in diffuse Hα do not coincide with zones of high H I column density, a result which contradicts the predictions of the massive neutrino decay hypothesis. This lack of correlation is maintained if we smooth the Hα image to match the resolution of the H I image. The leaky H II region model, even in its simplest form as presented here, offers a much better solution.

In Fig. 4 we present the results of applying the simple geometrical propagation model to leaky H II regions in three regimes: constant escape fraction, density bounding only for $L_{H\alpha} > L_{Str}$, and the "mixed model" as described above, compared with the observed distribution of the diffuse Hα. It is clear that the model with density bounding only for $L_{H\alpha} > L_{Str}$ yields a worse fit to the surface brightness than the other two. On the basis of this result we can already begin to question the hypothesis put

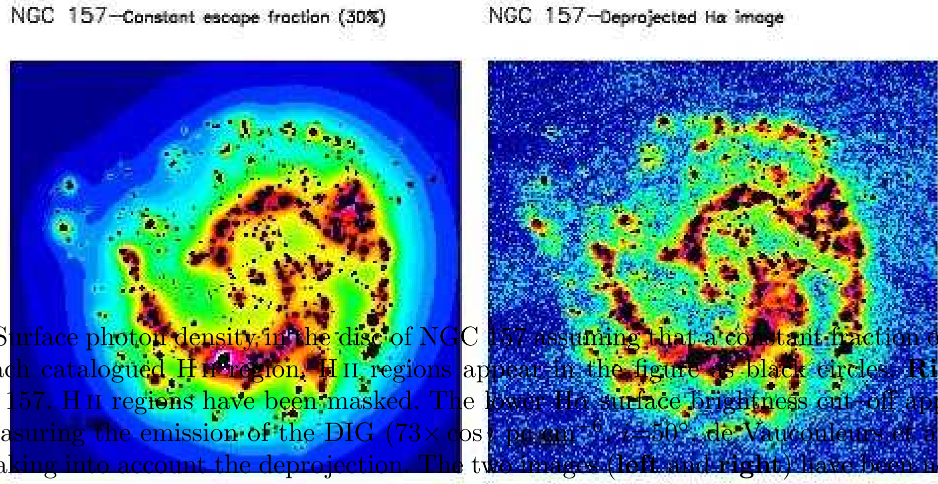

Fig. 3. Left: Surface photon density in the disc of NGC 157 assuming that a constant fraction of the ionizing photons escape from each catalogued H II region. H II regions appear in the figure as black circles. **Right:** Deprojected Hα image of NGC 157. H II regions have been masked. The lower Hα surface brightness cut-off applied to this galaxy in Paper I for measuring the emission of the DIG ($73\times \cos i$ pc cm^{-6}, i=50°; de Vaucouleurs et al. 1991) has also been applied here, taking into account the deprojection. The two images (**left** and **right**) have been normalized and plotted using the same colour scale.

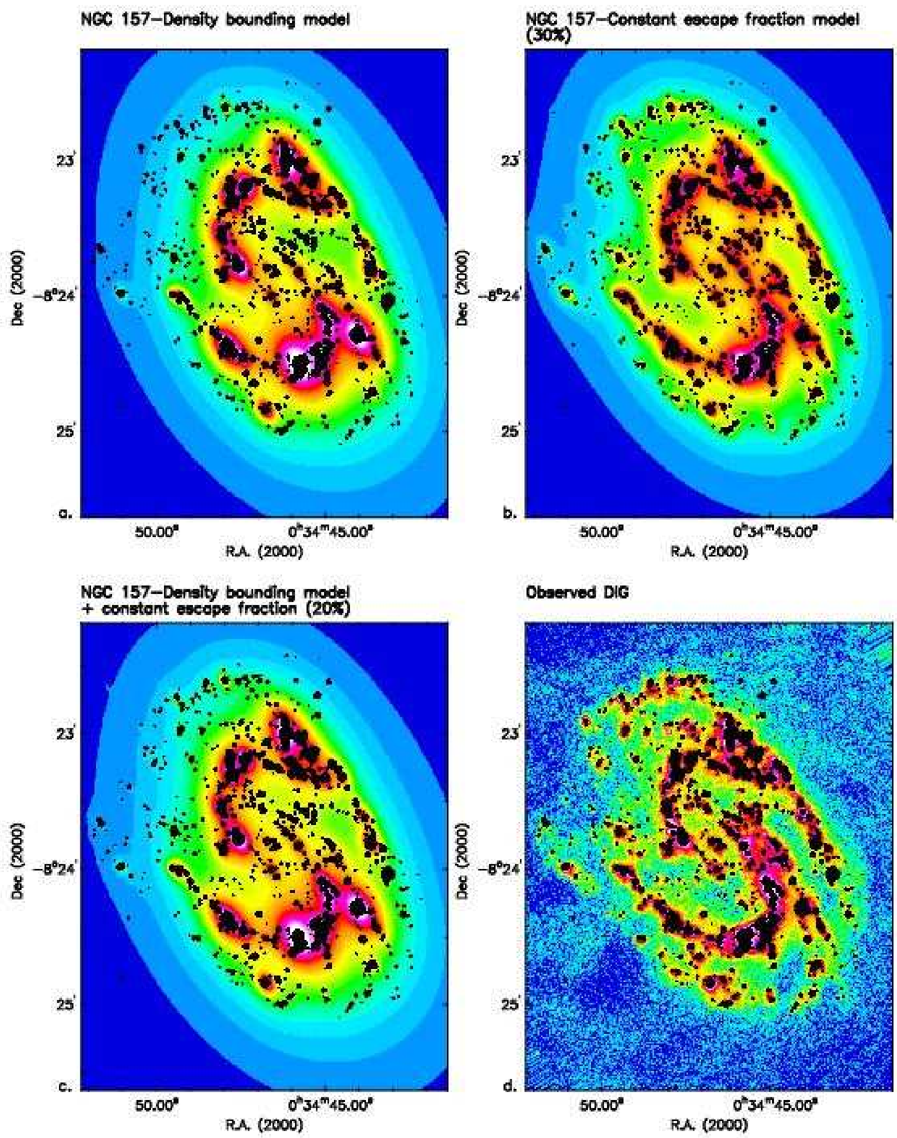

Fig. 4. Colour representation of the modelled ionizing photon density in the disc of NGC 157, assuming that this distribution is produced by the escaping photons from the most luminous regions alone (case B, **a.**), from all the catalogued H II regions (case A, **b.**) or from all H II regions but with different escape fractions (case C, **c.**). The images have been normalized to the mean value in the ellipse determined by the observed Hα emission of the galaxy (see Paper I). The observed DIG is shown in **d.** for comparison (also normalized).

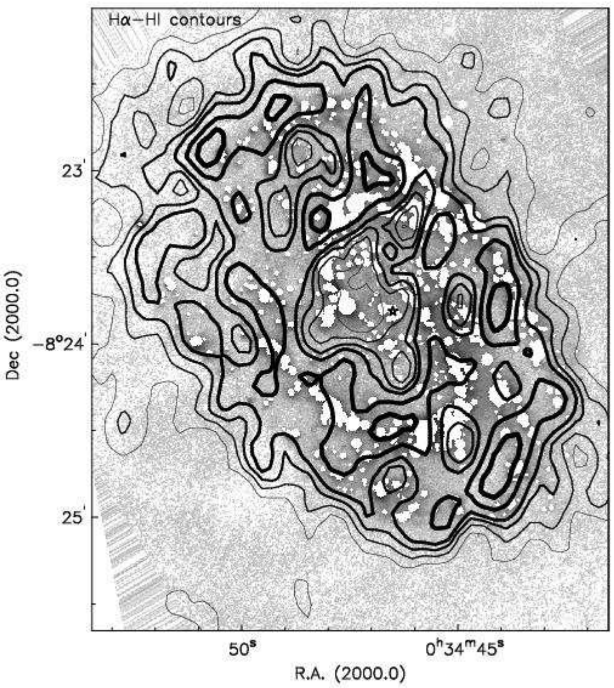

Fig. 5. Hα surface brightness density of the observed DIG in NGC 157 with H I column density contours superposed. The density contours are 1.45, 2.90, 4.35, 5.80, 8.70, 11.60 $M_\odot/pc^2$ (column density increasing from finer to thicker contours). The two quantities (Hα surface brightness and H I density) should be proportional in the "Sciama neutrino" model. We can see that (in spite of the difference in resolution between the two images) the H I distribution does not correlate at all with the Hα emission by the DIG. Darker areas in the image correspond to higher levels of Hα emission by the DIG of the galaxy. Thicker contours represent the higher H I column densities. The parallel shading in the corners of the image is an artifact generated in the rotation of the image to obtain the correct orientation (the same effect is seen in Figs. 4d, 7d, 8 and 9).

forward in Beckman et al. (2000), that only those regions with $L_{H\alpha} > L_{Str}$ are density bounded. This is particularly clear for the diffuse emission from the group of H II regions forming the uppermost arm of NGC 157. Although most of these regions have $L_{H\alpha} < L_{Str}$ the arm is surrounded by diffuse emission, which is not well reproduced in the "density bounding" model where Lyc photons escape only from the regions with $L_{H\alpha} > L_{Str}$. In all the models the distribution of the diffuse emission is less confined to the zones around the arms than in the galaxy as observed, and this leads us to conclude that the underlying assumptions are rather too simplified.

4.2. Models incorporating the observed H I column density distribution

One of the simplifying assumptions implicit in the results of Fig. 4 is that the H I which down–converts the escaping Lyc photons to Hα is in a disc of uniform thickness. We carried out a check to see whether at least part of the discrepancy between models and observations could be attributed to this. In Fig. 6a,b,c, we show ratios of the modelled Hα surface brightness to the observed surface brightness, for the three cases presented in Fig. 4. The ratios are those of Figs. 4a,b and c, respectively, divided by Fig. 4d, and smoothed to four times the original pixel size. In Fig. 6d we have shown the measured H I surface density for comparison. We note that the zones where the ratio of predicted to observed Hα is high in Figs. 6a,b,c, coincide with the zones where the observed H I column density is low in Fig. 6d, which implies that our neglect of the H I column density variations in our model predictions of Fig. 6 needs to be corrected. We have performed such a correction, again in the simplest way possible, by multiplying directly the predicted Lyc field in a model by the H I column density. The results are shown in Fig. 7 where we can see that, globally, the distribution of Hα from the DIG is better reproduced in general than in Fig. 4, in that the diffuse component is more intense closer to the arms, and less so, further away. However in one aspect the "H I corrected" models reproduce the oberved DIG less well than the previous ones, i.e. in the zone around the centre of the galaxy, where the predicted intensity is too low in the H I corrected models. One reason for this is that we have simply assumed that the Hα emission ought to be linearly proportional to the H I column density. This would be a fair approximation only if the H II column density were small compared to that of H I; if not it would seriously under–estimate the predicted Hα. We carried out a test for this, illustrated in Fig. 8, in which we first estimated the H II column density, and then compared it with that of H I. Since we measure directly a surface brightness, i.e. an emission measure (in Hα) our estimate of the column density cannot be unique, without a further assumption, which is the effective thickness (h) of the Hα emitting layer. Unfortunately the result depends on the square root of this thickness, which cannot be measured. In Fig. 8 we have used 900 pc for this thickness, taking the "Galactic Reynolds layer" as our guide. Fig. 8a maps the resulting H II column density in the DIG, and in Fig. 8b we have divided this into the observed H I column density, yielding a map of H I/H II. We see from this map that the ratio is between 5 and 15 over most of the galaxy disc, but that near the centre it drops to low values, so that we would expect our H I–corrected models to fall short of the observed surface brightness in Hα near the centre, as found in Fig. 7.

One problem in allowing for the H I in this modelling process is that the angular resolution in the H I map of

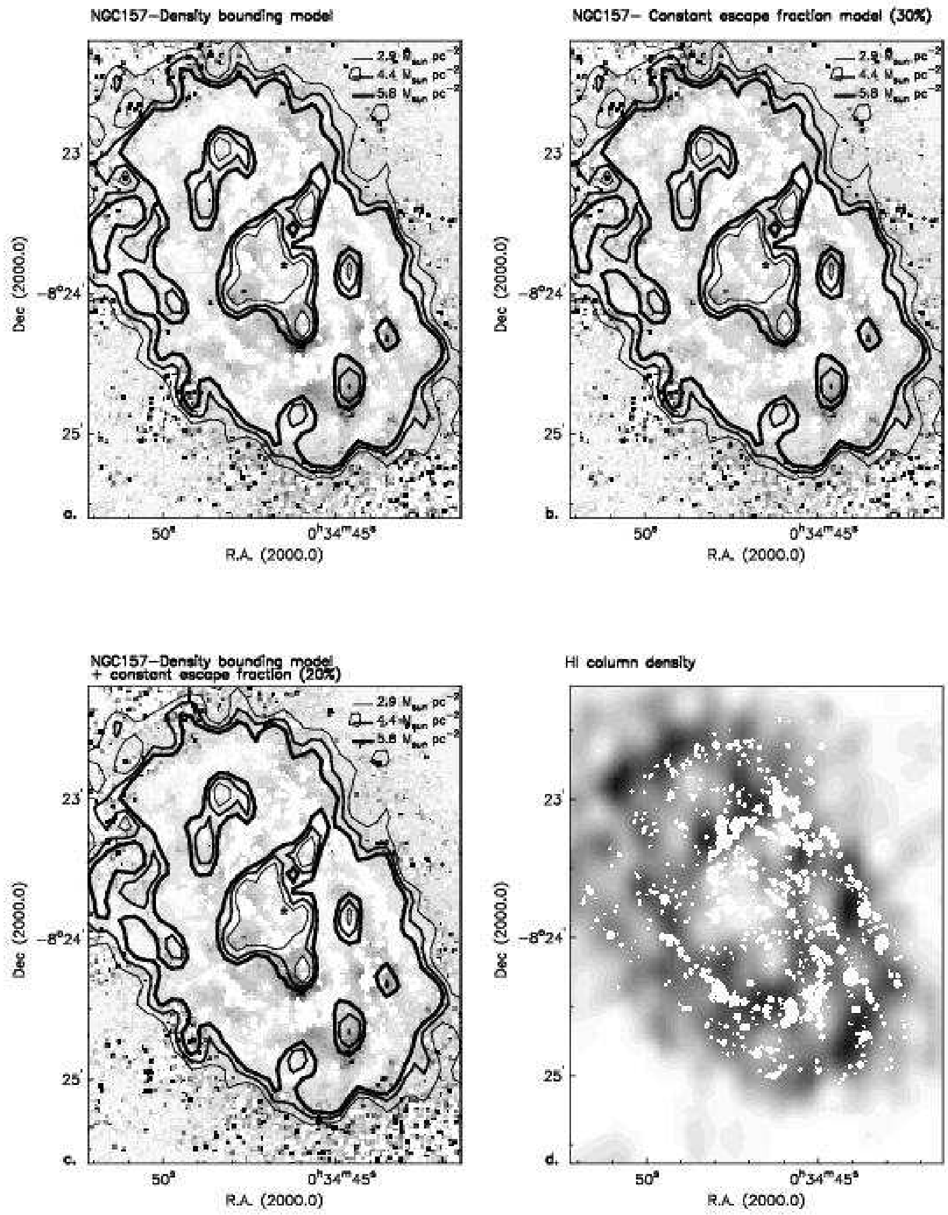

Fig. 6. First three panels: ratio of the modelled photon distribution, for the three cases shown in Fig. 4a,b,c, to the observed DIG emission in Hα. Pixels have been binned to a new pixel size equal to 4. Only the lowest H I density contours have been superposed (cf. Fig. 5 and panel d.) There is good spatial coincidence of the zones where the models with an assumed layer of H I of constant thickness overestimate the emission (high ratios correspond to darker areas), with the "holes" in the measured H I distribution. This distribution is shown in grey scale in the fourth panel, in which the darkest areas correspond to the highest H I column densities.

NGC 157 is no better than 12″, which is a factor of 15 lower than we would wish, in order to make adequate use of our Hα map. In spite of this we have gone one step further in our modelling, taking into account the absorption by the intervening medium of the propagating Lyc field. This is done by substituting Eq. 11 by

$$\begin{aligned} I_j(x,y) &= \frac{D_j}{4\pi[(x-x_j)^2+(y-y_j)^2]}\exp\left(-\tau_j\right) = \\ &= F_j \exp\left(-\tau_j\right) \end{aligned} \qquad (13)$$

in which F_j is the flux incident on unit path length at (x, y) from a source j, and τ_j is the optical depth along the path to (x, y), which is the integrated product of the effective volume absorption coefficient (k) and the volume density (ρ_{HI}) along the path between the emitting H II region j and the point (x, y). In implementing this model, the effective absorption coefficient is taken as an empirical parameter, which includes absorption by the H I (the cause of the Hα emission) and also dust extinction, with an assumed constant dust to gas ratio.

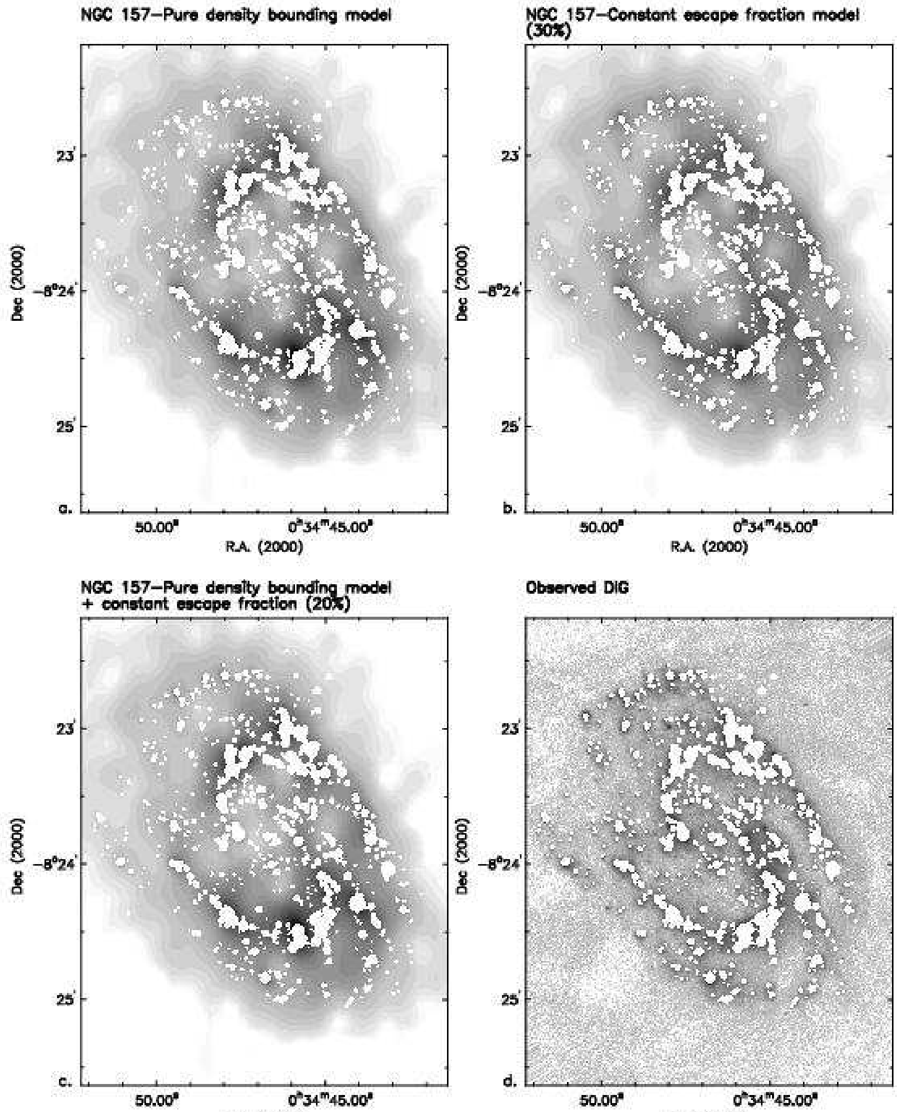

Fig. 7. Monochrome representation of the modelled diffuse Hα emission for the galaxy NGC 157. Each figure represents the product of the photon distribution and the H I density at each point of the galaxy for the cases B, A and C shown in Fig. 7. All four figures have been normalized to the mean value in the ellipse determined by the observed Hα emission of the galaxy and plotted using the same grey scale. The different resolutions between the Hα and the H I data does not allow us to extract a definitive conclusion from these maps, but the broad agreement in the overall DIG distributions predicted with that observed, strongly favours the hypothesis that photons leaking from H II regions do power the DIG (see Sec. 5 for a discussion).

Using Eq. 13 we can express the decrement, dI_j/ds of ionizing radiation per unit length ds at the point (x,y) by

$$\begin{aligned} \frac{dI_j}{ds} &= \frac{dF_j}{ds}\exp\left(-\tau_j\right) + F_j\frac{d\exp\left(-\tau_j\right)}{ds} = \\ &= \frac{dF_j}{ds}\exp\left(-\tau_j\right) + (-k\rho_s)F_j \end{aligned} \tag{14}$$

The first term here represents the decrement due to geometrical dilution, and the second term the component due to absorption, both terms being intuitively clear. In order to get a reasonable value of k without three–dimensional modelling of the clumpy medium, we take an empirical approach based on the observation that the diffuse component extends to distances of order 0.5 kpc from the concentrations of H II regions. With this starting point we take a trial value of k as that which would reduce a flux to 1% of its initial value over a range of 500 pc. Taking an average H I scale height of 100 pc as a constant value over the disc and a mean column density in the disc as that observed: 8.6×10^{20} cm^{-2}, we find a value for k of 5.3×10^{-22} cm^2, or more generally $5.3\times10^{-22}\times z_{100}$ cm^2, where z_{100} is the value of the scale height in units of 100 pc. In fact, this value for k ought to be an upper limit, because the condition that the flux be reduced by a factor 100 over a distance of 500 pc is a stronger condition than that required by the empirical map of the DIG. In our numerical

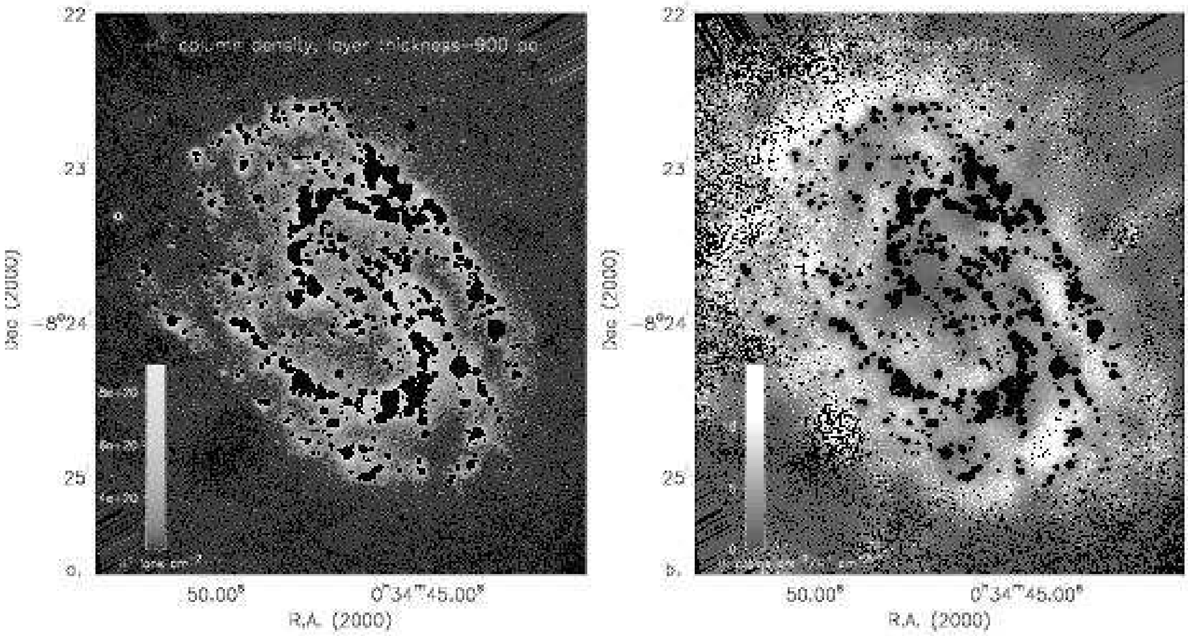

Fig. 8. a. H^+ column density map assuming an effective thickness of the Hα emitting layer (h) equal to 900 pc. Since the ionized mass per unit area is given by: $m(\mathrm{H}^+) =< N_e >_{rms}\, m_H h$ and the emission measure EM$=< N_e >^2_{rms}\, h$, the relation between the number of ionized atoms of H^+ per cm^2, $n(\mathrm{H}^+)$, the EM and h is given by: $n(\mathrm{H}^+) = \sqrt{\mathrm{EM}} h^{1/2}$. The mean value for the DIG is $\sim 5 \times 10^{20}$ H^+ ions cm^{-2}. For other scale heights the monochrome bar calibration changes by a factor $(\frac{h}{900pc})^{1/2}$. **b.** Ratio of the H I column density to the H^+ column density assuming an H^+ effective layer thickness equal to 900 pc in the disc of NGC 157. In spite of the different image resolutions, in the DIG area most distant from H II regions (where surface brightness gradients are nearly constant, see Paper I) the figure will give a reasonable estimate of the ratio of the two column densities. In these areas, the H I column density is between 5 and 12 times greater than the H^+ column density.

models we took values of k ranging between 5.3×10^{-24} and $5.3 \times 10^{-22} \times z_{100}$ cm^2.

Our models are of two kinds: mixed models in which the absorption coefficient k is allowed to vary, but in which the H I is assumed to take the form of a disc of constant thickness, and models in which an optimized value for k is combined with the observed H I column density map. The two types of models are illustrated in Figs. 9 and 10 respectively. In Fig. 9 we can see that the best approximation to the observed DIG surface brightness distribution is found using an empirical coefficient $k = 5.3 \times 10^{-23} \times z_{100}$ cm^{-2}, and in Fig. 10 we can see the results of using this value with two different assumptions about the Lyc escape fraction: a constant escape fraction and a constant fraction below $L_{H\alpha} = L_{Str}$, and a rising fraction for higher H II region luminosities (cases A and C respectively) . The results shown in Figs. 9 and 10 illustrate the fact that we are finding it difficult to obtain real improvements in our results with increasingly refined assumptions. Perhaps Figs. 9b y 10b between them give the closest reproductions of the observations (e.g. Fig. 9d), and seem to indicate that a constant escape fraction for all the regions gives the best fit to the observed DIG. However there are a few necessary cautionary statements to make. We can see that Fig. 10b, in which the fullest set of assumptions has been brought in: Lyc field modified by absorption, and emission in Hα proportional to the H I column density, gives a clearly inferior reproduction of the DIG morphology than Fig. 9b, assuming a constant H I column density. This is due to two effects, firstly the H I column density should not be used in this way where the H II column is a major fraction of the total H column, as occurs near the centre of NGC 157 (see Fig. 8 and discussion in Sec. 5). Secondly, we are coming up against the limits imposed by the relatively poor angular resolution in the H I map. This is not so important far from the sources, where the Lyc field gradient is low, but is critical close to the H II regions, and means that models with any further degree of refinement cannot be properly empirically tested. The combination of these two effects can be already leading to misleading conclusions in

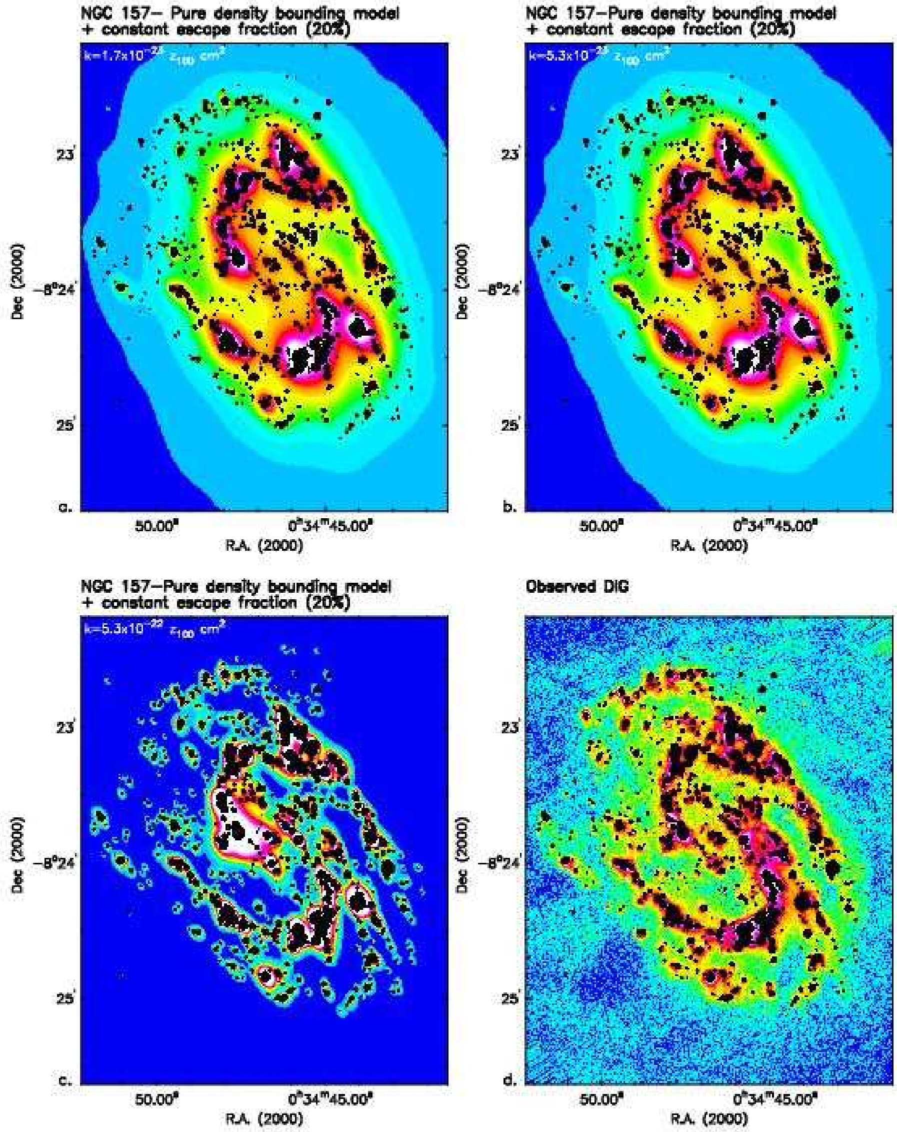

Fig. 9. Same as Fig. 4 but for models including absorption by neutral hydrogen. In this case, all figures assume case C (mixed model) for the escape fraction of ionizing photons. The effective volume absorption constant for each case is shown in the left top corner of each representation.

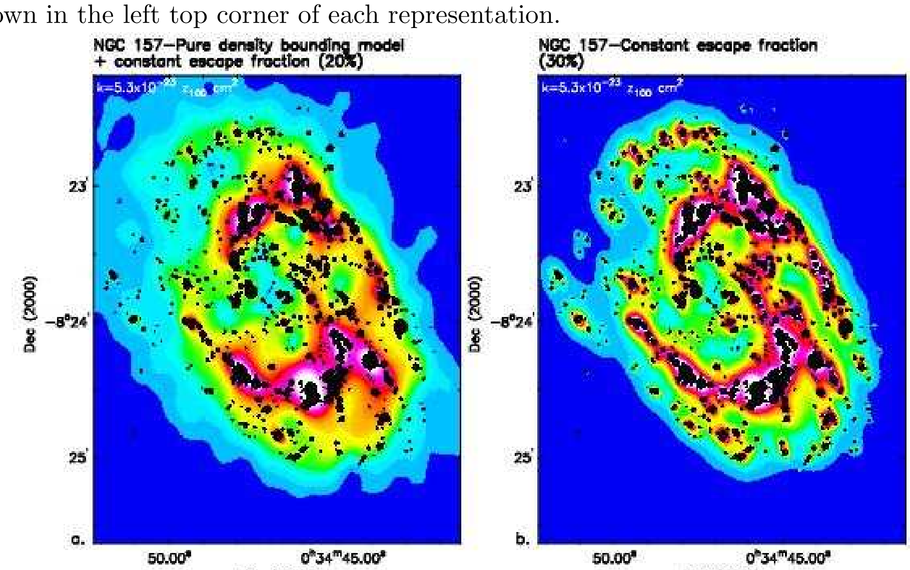

Fig. 10. Same as Fig. 7, but for models including absorption **a.** for the mixed model and **b.** for the constant escape fraction model.

terms of the fine detail. An apparent defect in those models where the high luminosity regions have an increasing Lyc escape fraction is that the predicted Hα near these regions is higher than that observed. Such an effect would be expected if the H II/H I column density near the regions was raised (the same effect that we see close to the centre of the galaxy in the constant H I thickness model of Fig. 4a,c) due to the ionization itself. The effect could be detected only with H I resolution of order $1''$, i.e. comparable to that in Hα. In the absence of such data we are in no position to detect the effect, so the impression that the constant escape fraction models are better than the mixed models could well be an incorrect interpretation.

Table 1. Lyc continuum photon flux escaping from the H II regions in NGC 157 predicted by the models considered here, to be compared with the Lyc flux (bottom line) required to maintain the DIG in this galaxy ionized, assuming case B recombination and T$\sim 10^4$ K (Paper I).

Model/observation	$\mathbf{10^{52}}$ Lyc phot s^{-1}
Density bounding (constant ϕ)	14.8
Density bounding (constant ρ)	29.4
Constant escape fraction 30%	6.81
Mixed model	15.8 − 30.4
Required Lyc flux	12 − 19

5. Discussion and conclusions

We have used a modelling technique to examine the hypothesis that the H II regions in disc galaxies are sufficiently leaky that they allow the ionizing photons from their OB stellar populations to escape with intensity high enough to produce the diffuse Hα observed across the disc of a galaxy. We have used NGC 157 as a test object here, because one of the observational elements required in the models is a map of the H I column density of the object to complement an existing map in calibrated Hα surface brightness. A second element in the modelling process is to derive a catalogued intensity calibrated map of the individual H II regions in Hα, complemented by the measured surface brightness over the full diffuse component. These data are not trivial to acquire, and for the galaxies for which we had carried out calibrated Hα mapping of the necessary precision, only NGC 157 had an available map in H I of anything approaching adequate angular resolution. In spite of the approximations and data limitations mentioned freely at the relevant points in the text, we have found a very fair coincidence between the distribution of ionizing photons, and the H$^+$ distribution across the face of NGC 157, as shown in Figs. 4, 7, 9, and 10. This leads us to conclude that in spite of the simplicity and the approximations with which the models have been generated, and the low angular resolution of the H I data, the hypothesis that the ionization of the DIG in NGC 157 is caused by the Lyc photons escaping from the H II regions does receive major support from this exercise.

The fact that the hypothetical model based exclusively on the H I distribution, and designed as a test of the Sciama neutrino decay theory (Fig. 5) gives such complete disagreement with the observed Hα distribution in the DIG not only serves as a further rebuttal of this theory, but points up the rather good agreement of the models using leaky H II regions as the ionizing sources.

In order to estimate quantitatively the goodness of the models we performed a series of numerical tests. These consisted of an analysis of the residuals obtained when subtracting the observed Hα emission of the DIG from the modelled emission (both observations and models normalized as explained, e.g. in Fig. 4) via histograms showing the intensity distribution of all the pixels in these images of residuals. This method allowed us to discriminate between rather poor solutions (such as the Sciama model cited above) or random Hα intensity distributions used as trials) and reasonably good solutions, which cover most of the cases in which the Lyc photons escape from the H II regions.

However, it is much more difficult using formal statistical tests to reach a firmer conclusion about which of the assumptions about the escaping fraction of ionizing photons yields the best fit to the observations. The models which give low residuals are also those that seem to offer a better result by simple eye estimates, whereas those which give higher and more asymmetrically distributed residuals are also worse under visual inspection.

Direct inspection of the figures, and consideration of the corresponding residual histograms give sufficient grounds to reject the models with the highest values of the empirical extinction coefficient: $k \gtrsim 5.3 \times 10^{-23} \times z_{100}$ cm^{-2}, while the model which assumes that photons escape only from the most luminous regions, those with $L_{H\alpha} > L_{Str}$, does not predict sufficient intensity in the DIG near the northernmost arm of the galaxy. Here the majority of the regions have $L_{H\alpha} < L_{Str}$ but a measurable surface brightness is measured in the DIG surrounding the arm. It is clear that flux must be escaping from regions with $L_{H\alpha} < L_{Str}$, a result found also in models where extinction was not considered. Very good fits to the observed DIG surface brightness distribution are found in those models where we have taken a constant escape fraction for the Lyc photons. This appears to go against our hypothesis, previously put forward to explain the form of the H II region luminosity function in Hα (Beckman et al. 2000; Rozas et al. 1996a, 1999, 2000) that H II regions with $L_{H\alpha} > L_{Str}$ are the principal sources of ionization of the DIG. However our models with a constant escape fraction of the ionizing photons down–converted to Hα, are normalized and yield maps with only relative intensity isophotes in Hα. To fit the total integrated luminosity in

the DIG of NGC 157 a constant escape fraction of 70% would be required (see Table 1), and this seems improbable from a range of physical considerations governing the escape of Lyc photons from star forming regions. Therefore it seems that if a constant fraction of ionizing photons is escaping from the H II regions, other principal ionizing sources (rather than H II regions) would be needed in order to explain the power requirements to ionize the DIG (Table 1).

However, fits of very good quality are also found from models with a constant escape fraction of ∼20% for low luminosity regions and an increasing fraction for those regions with $L_{H\alpha} > L_{Str}$, and this would be in better accord with our deductions from luminosity functions and H II region central surface brightnesses (Beckman et al. 2000).

We should note here, that other ionizing sources may contribute to the ionization of the DIG, and the aim of this paper is not to demonstrate that the H II regions are the only ionizing source of the DIG. However, the results presented give strong support to the hypothesis that H II regions are an important source and probably the main source for the ionization. Known possible ionizing sources for the DIG in normal galaxies include photoionization (by supernovae, Wolf-Rayets, white dwarfs, cosmic rays, X-rays, or field OB stars for example, Hoopes & Walterbos 2000), but also shocks and turbulent dissipation in the ISM (e.g. Rand 2000; Walterbos 1999) may be important in specific zones, as has been noted within the Galaxy (Tufte, Reynolds & Haffner 1999). Contributions from such sources to the general ionization of the DIG are not excluded by the evidence presented here.

To go further, reliably, into the problem would require an effort of detailed modelling of transport in a fully three–dimensional clumpy medium, plus the acquisition of an H I map of sufficiently high angular resolution. The limited conclusion of the present study is that the scenario in which leaky H II regions provide the ionizing sources which yield at least the major fraction of the Hα in the DIG appears to be well supported in the case of NGC 157.

Acknowledgements. This work was supported by the Spanish DGES (Dirección General de Enseñanza Superior) via Grants PB91-0525, PB94-1107 and PB97-0219. The WHT is operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

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